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Quarterly Report #3

The Reliability of Laser Reflowed Sn-Ag Solder Joints

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3.1 Thermomechanical Fatigue of Solder Joints in Electronics Packages

The greatest concern regarding reliability of solder joints is thermomechanical fatigue (TMF). TMF results from constrained temperature changes in the environment of the electronic package and/or temperature gradients induced by power cycling of the package. Typically, electronic packages and substrates have different thermal expansion coefficients, so temperature changes result in elastic strains in the package and substrate and elastic/plastic strains in the solder joining the two together.

Figure 3.1 shows a schematic of a typical electronic package. The component might be a discrete resistor or encapsulated Si wafer. The substrate could be a reinforced polymeric printed circuit board or the thick ceramic substrate of a multichip module. Regardless, the response of the solder to the given thermal cycle is dependent upon the thermal and mechanical properties of the component and substrate. In Figure 3.1a, the assembly is at a temperature of T_o and under zero stress. The response of the system to temperature changes such as those shown in Figure 3.1b will be between the limits of infinitely stiff beams representing the component and substrate, Figure 3.1c, and very compliant beams, Figure 3.1d.

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The mechanical response of the system to a finite temperature change under these limiting conditions is represented in Figures 3.1c and 1d. In Figure 3.1c, the fully constrained (fc), or infinitely stiff condition, is shown. The displacement in the solder for this condition is given by $L \cdot \Delta T \cdot \Delta\alpha$, with $\Delta\alpha = \alpha_A - \alpha_B$, whereas in the highly compliant condition, shown in Figure 3.1d, there is negligible strain in the solder joint. The wide array of electronic components and substrates in use today represent an almost infinite variety of mechanical and thermal conditions under which solder joints are expected to perform a critical role in both mechanical attachment and electrical connection.

This work aims at measuring the thermal cycling fatigue life of solder joints which interconnect materials of mismatched thermal expansion coefficients. The parameters of primary importance are the relative stiffnesses of the materials to be joined and the thermal expansion mismatch. Stress and strain in the solder joint are monitored continuously during testing as the temperature changes by monitoring strain in the (elastic) materials that are joined and by accounting for the stiffness of these material elements. Initially, a specific thermal cycle is used to evaluate the thermomechanical fatigue (TMF) life of the solder joints, but other temperature cycles may be investigated if deemed useful.

This work is directly applicable to evaluating the TMF life of solder joints in electronic packages. Package geometries and the materials used in the packages vary widely. This work is especially important because the use of the most commonly used solder alloy, eutectic Sn-Pb, may soon be restricted or completely banned in electronics assemblies for environmental reasons. The eutectic Sn-Ag solder alloy investigated has a melting point of 221°C. It is a high potential candidate to replace eutectic Sn-Pb solder in the most demanding applications where service temperatures are high, e.g., under the hood in automobiles and in avionics systems.

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3.2 The Model

Figure 3.2 shows a schematic representation of an analog mechanical system to the electronic package where the spring represents the combined stiffness of the package and substrate. The shear displacement of the solder joint, $l_{sold,}$ will at any time be equal to:

$$l_{sold} = l_{th} - l_{mech} \tag{3.1}$$

l_{th} is the thermal expansion length mismatch of the assembly defined by:

$$l_{th} = L\,(T - T_o)\,(\alpha_A - \alpha_B) \tag{3.2}$$

where L is the distance between the solder joint and the neutral point in the package, T is the immediate temperature, T_o is the reference temperature, and α_A and α_B (see Figure 3.1) are the thermal expansion coefficients of the electronic assembly components. l_{mech} is defined as:

$$l_{mech} = P / k \tag{3.3}$$

where P is the shear force imposed by the electronic assembly on the solder joint and k is the stiffness of the assembly.

If the solder joint in Figure 3.1 is assumed to have constant height, h, and cross sectional area, A, the shear stress and shear strain in the solder, and the thermal strain imposed by the assembly, are:

$$\tau_{sold} = P / A \tag{3.4}$$

$$\gamma_{sold} = l_{sold} / h \tag{3.5}$$

$$\gamma_{th} = l_{th} / h \tag{3.6}$$

If Equations (3.1) and (3.4) are substituted for l_{mech} and P, respectively, in Equation (3.3), the solder stress may be expressed as a function of the assembly stiffness and solder and thermal displacements as:

$$\tau_{sold} = \left(\frac{k}{A}\right)\left(l_{th} - l_{sold}\right) \tag{3.7}$$

Furthermore, if Equations (3.2) and (3.5) are substituted for l_{th} and l_{sold} in Equation (3.7), rearrangement of terms yields the following linear relation between solder stress and strain:

$$\tau_{sold} = \left(\frac{k \cdot h}{A}\right)\left(\gamma_{th} - \gamma_{sold}\right) \tag{3.8}$$

A and h in Equation (3.8) are assumed to be constant, so a reference assembly stiffness, k', is defined as:

$$k' = \frac{k \cdot h}{A} \tag{3.9}$$

Substitution of Equation (3.9) into Equation (3.8) yields:

$$\tau_{sold} = k'\left(\gamma_{th} - \gamma_{sold}\right) \tag{3.10}$$

The shear stress in the solder joint will at any time be equal to the difference of the solder and thermal strain components multiplied by the reference assembly stiffness.

3.3 Thermomechanical Hysteresis

At a given temperature, γ_{th} is set by the material/geometric elements comprising the joint system. Therefore, according to Equation 3.10, γ_{sold} and τ_{sold} must exist on a line of slope k' in a solder stress-strain plot. This is illustrated in Figure 3.3a which contrasts creep, stress relaxation, and the present situation of "stress reduction" [1,2]. Also, at a **specific** temperature, the solder stress and strain must exist on a **specific** stress reduction line as shown in Figure 3.3b. At a given temperature, stress will always reduce towards zero. The slope of the stress reduction line is not necessarily constant, however. If the elastic moduli of the component or electronic package materials are temperature dependent, then the slope of the stress reduction lines will vary accordingly.

A set temperature excursion ($\Delta T = T_{max} - T_{min}$) defines the fully-constrained shear strain range, γ_{fc}, in the solder joint, given by:

$$\gamma_{fc} = L\,(\Delta T)\,(\Delta\alpha) / h \tag{3.11}$$

If infinitely stiff beams (as in Figure 3.1c) are used or are assumed to exist, the strain in the solder joint for the given temperature cycle will be equal to the fully-constrained strain range. If anything other than infinitely stiff beams are used, the strain in the solder joint will be correspondingly less than γ_{fc}. Thermomechanical stress-strain hysteresis, under the conditions described above, is then bounded by the relation:

$$\tau_{sold} = k'\left(\gamma_{fc} - \gamma_{sold}\right) \tag{3.12}$$

where γ_{sold} may vary anywhere within the range of values encompassed by γ_{fc}. The maximum attainable stress is $k' \cdot \gamma_{fc}$, which may be attained only at temperature extrema. A stress equal to k' may be attained only when γ_{fc} is greater than or equal to 1.0 (100% strain).

The fully-constrained strain range and the sample stiffness form the bounding conditions for thermomechanical stress-strain hysteresis. Figure 3.4 illustrates this point. For a given assembly and joint configuration, the fully-constrained strain range, γ_{fc}, is set by the temperature excursion. Assignment of the zero point of strain is arbitrary, but, for consistancy may be defined by the as-soldered, stress-free condition. In Figure 3.4, the stiffness line which crosses the stress-strain origin (0, 0) is the 2°C stiffness line. This implies that the test was started at 2°C in a stress free condition or that the test was started at some other temperature under stress. The other sample stiffness lines drawn in Figure 3.4 correspond to the temperature extrema. These stiffness lines form the boundaries of stress in the hysteresis.

The SnAg solder alloy that is being studied here has a melting point of 221°C and will be tested at temperatures between -15°C and 125°C. These correspond to homologous temperatures of approximately 0.52 and 0.80, respectively. Clearly the mechanical behavior of the solder joint will be very temperature dependent under these varying conditions. This is apparent in the typical hysteresis loop shown in Figure 4 collected from an Sn-Ag solder joint.

At point A of Figure 3.4 (the end of the low temperature hold period), the temperature ramp-up begins. Stress approaches the zero point during ramp-up as γ_{th}

approaches γ_{sold} (see Equation 10). At 60°C $\gamma_{th} = \gamma_{sold}$ and the stress direction reverses. At B, 105°C, the solder joint begins to strain plastically under the increasing stress and temperature. At the high temperature hold, C, 125°C, stress "reduces" (combined creep and stress relaxation). During temperature ramp-down, the stress direction reverses and at sufficiently high stress, D, 50°C, the solder joint strains plastically in the opposite direction.

Figure 3.5 shows a detail of the low temperature region of the hysteresis shown in Figure 3.4. At point E, the test assembly and solder joint reach -15°C. Time dependent strain in the solder is still evident even at -15°C. The average stress on the solder joint at the low temperature hold is approximately 14.6 MPa. The average strain rate under these conditions was calculated to be -1E-5 /sec. At the end of the low temperature hold, A, the ramp-up begins. The rapid positive 0.15% increase in strain indicated after point A in Figure 3.5 may be due to unequal heating rates in the soldered materials. Following this small anomaly, the solder returns to straining plastically in the negative direction in spite of the decreasing load and positive elastic contribution to total strain. The most likely explanation for the atypical negative strain during ramp-up is that time dependent strain is occuring under the shear load. This has been observed previously in thermal cycling experiments performed on Sn-40Pb and Sn-3Cu solder joints [1,3,4].

There are many mechanical and metallurgical details of thermomechanical hysteresis and fatigue that when better understood should enable the engineer to better predict the TMF lifetime of solder joints and prolong the lifetime through better electronic package design and solder alloy modification. The present study will focus on measuring the thermomechanical hysteresis and fatigue lifetime of Sn-Ag eutectic solder joints as a function of k' and γ_{fc}. Metallurgical examination of solder joints cycled to intermediate numbers of thermal cycles will be used to explain the evolution of the hysteresis.

References

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4. Y.-H. Pao, S. Badgley. E. Jih, R. Govila, and J. Browning, "Constitutive Behavior and Low Cycle Thermal Fatigue of 97Sn-3Cu Solder Joints," J. Electronic Packaging, 115 (1993) 147.

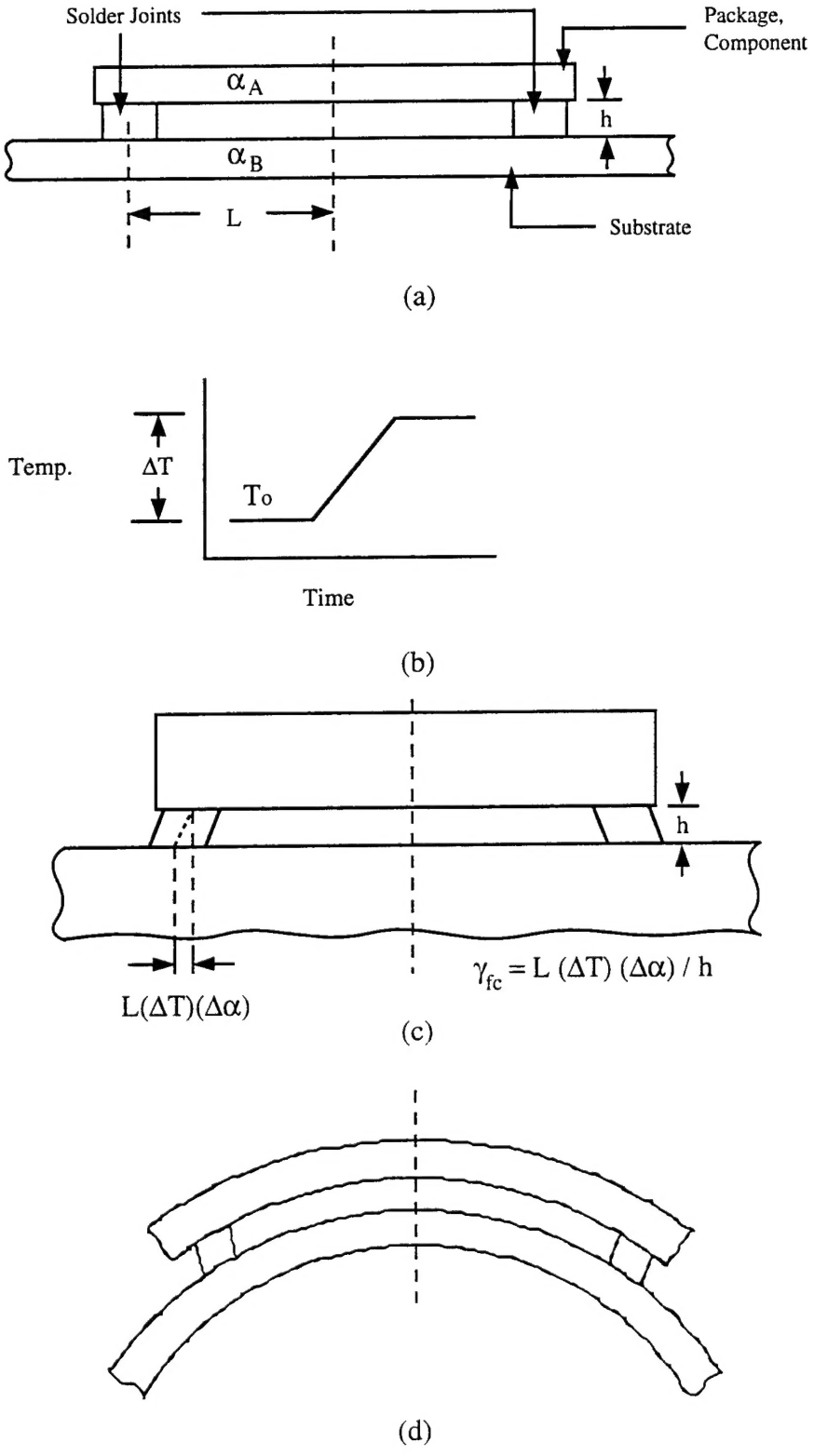


Figure 3.1. Representative schematic of electronic package and its response to a change in temperature: a) stress-free assembly at To, b) temperature excursion, c) solder response in rigid, fully-constrained (fc) assembly and, d) response of compliant assembly. Note that all of the temperature induced strain appears only in fully constrained assemblies.

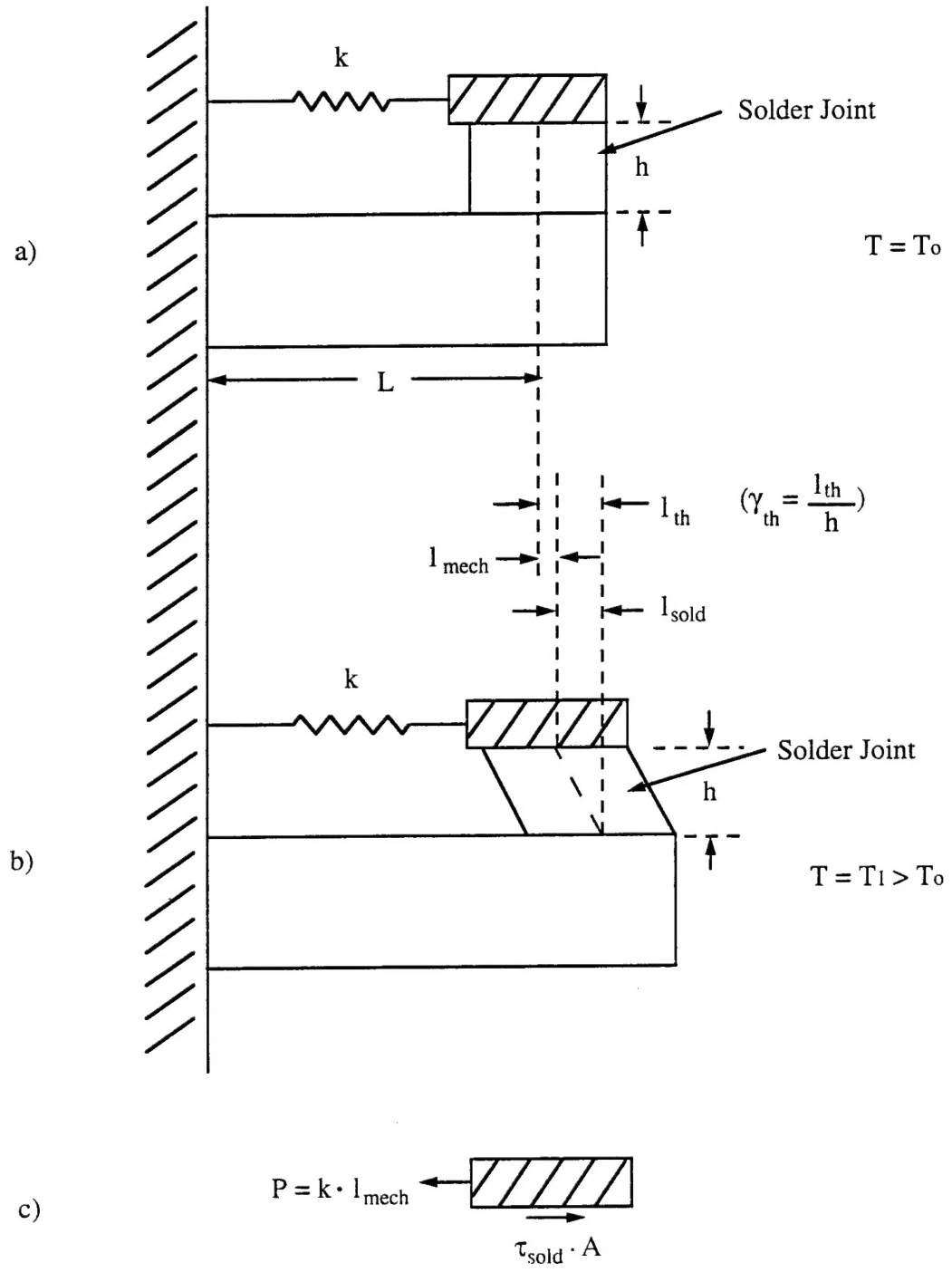
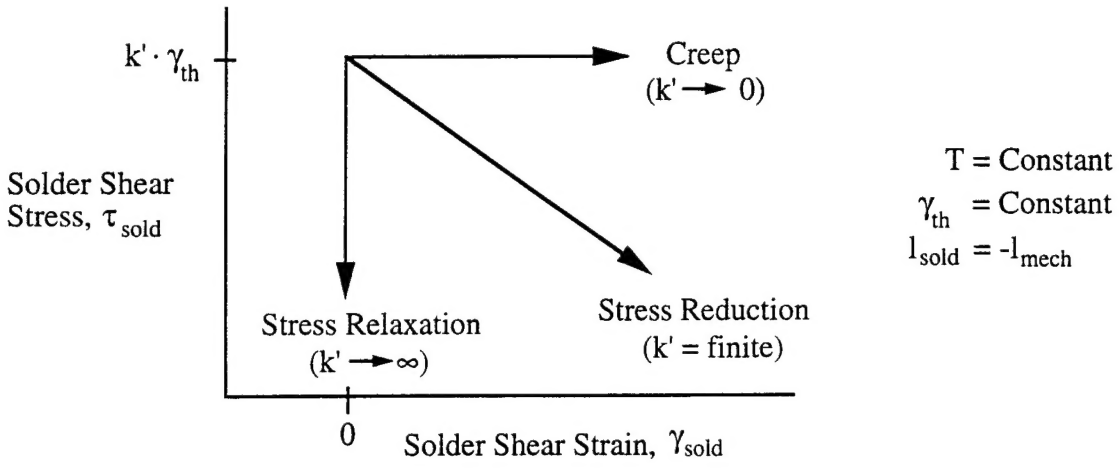
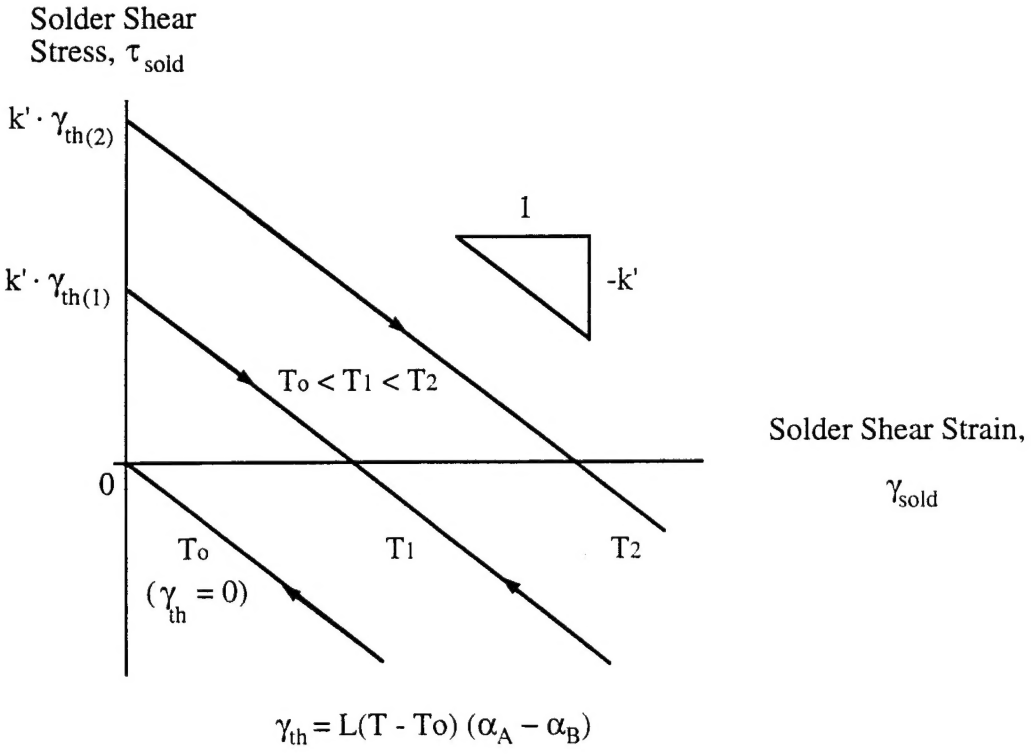


Figure 3.2. Schematic representation of an analog mechanical system to the average electronic package, a) system at the reference temperature, To, b) system following a temperature change, c) free body diagram.



(a)



(b)

Figure 3.3. a) Comparison of **isothermal** stress reduction to creep and stress relaxation, b) By setting the reference temperature a specific isothermal stress reduction line exists at every other temperature, but, k' need not be constant with temperature.

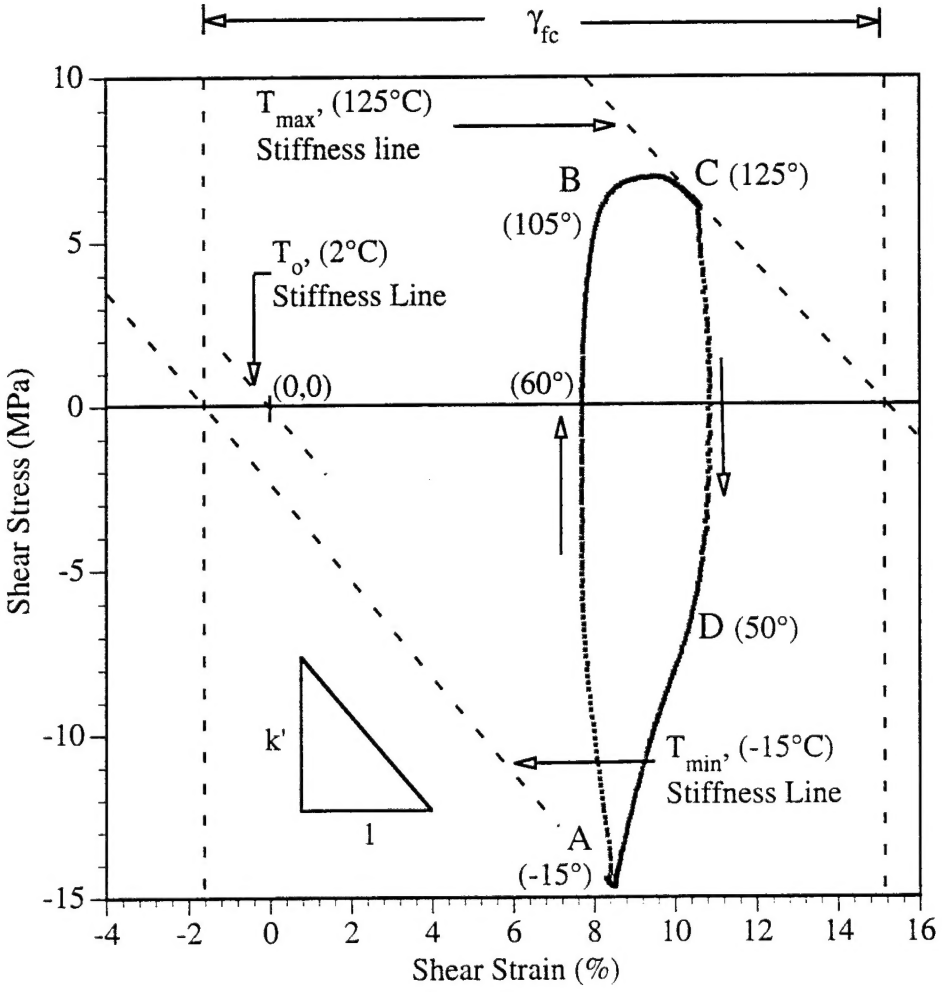


Figure 3.4. Thermomechanical stress-strain hysteresis of a solder joint.

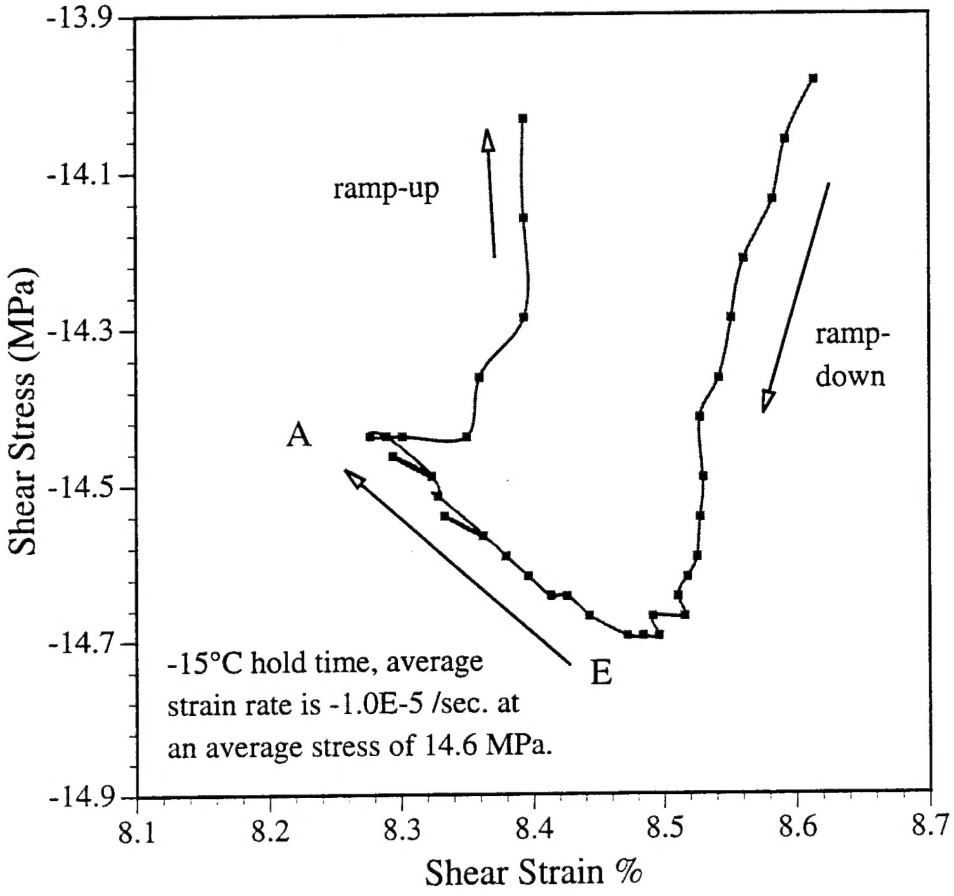


Figure 3.5. Detail of low temperature stress strain behavior from Figure 4 showing time dependent strain behavior even at the -15°C hold period, time between data points is 10 seconds.

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